APPENDIX R: Failure Modes Effects Analysis (FMEA)

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Failure Modes Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a systematic method for proactively evaluating facilities or a process to identify where and how they might fail; and to assess the relative impact of different types of failures. Once this is accomplished, the parts of the process that are most in need of change are identified. FMEA includes review of the following:

- Failure modes (What could go wrong?)
- Failure causes (Why would the failure happen?)
- Failure effects (What would be the consequences of each failure?)

A FMEA is often used to structure mitigation for risk reduction based on either failure (mode) severity reduction, or based on lowering the probability of failure's occurrence or both. FMEA is used to evaluate processes and facilities for possible failures and to prevent them by correcting the processes or design proactively, rather than reacting to adverse events after failures have occurred. This emphasis on prevention can significantly reduce risk of harm to human health and the environment. FMEA is particularly useful in evaluating a new process prior to implementation, and in assessing the impact of a proposed change to an existing process. FMEA provides a documented method for selecting a design with a high probability of successful operation and safety.

Tintina conducted its first FMEA evaluation early in the mine planning process. In this review they critically looked at the proposed operational processes and the design of facilities. The results of the FMEA evaluations were used to modify mining methods, milling processes and facilities for more effective, efficient and safer operations. The focus of these modifications was on minimizing risk to environmental resources and human health, while enhancing both environmental and operational performance and safety.

Objectives of this FMEA

The objective of this FMEA was to review failure modes and effects from historic mining industry standard methods of processes selection and facility construction, and use this review to develop mitigations for the identified failure modes. Once Tintina had developed a package of mitigations the two FMEAs (unmitigated and mitigated) were compared based on residual risk. Many of Tintina' proposed mitigations were innovative such as the selection of cemented backfill surface deposition of tailings while other layered various conventional construction methods into packages that significantly reduced risk to the environment, human health and the overall safety of facility construction and operation.

Method of Analysis

Two critical analysis need to be carried out before beginning a FMEA: identifying the cause of failures and the probability of their occurrence, and the ranking the severity of the potential impact of the failure.

Probability

The first step in developing a FMEA is to identify the cause of a failure mode and the likelihood of its occurrence. This is often done by examination of similar processes or construction methods and the failure modes that have been historically documented. A failure cause is looked upon as a design weakness. All the potential causes for a failure mode should be identified and documented. The probability of occurrence for various failure modes for this analysis over the 19 year mine-life included: unlikely (0), remote (0-1), infrequent (1-2), occasional (2-4), and likely (annually) and are specified in detail in Table 1. A failure mode is then given a probability ranking. In order to rank various failure modes probability criteria must be developed that explicitly define the range of failures to be compared and the range of frequency of occurrence for which they will be compared. Table 1 presents the probability table developed for criteria evaluated in these FMEAs.

Table 1. Probability of Occurrence Criteria for Ranking Failure Modes

Probability	Unlikely	Remote	Infrequent	Occasional	Likely
Description	Failure under these circumstances is unlikely	Failure is highly improbable due to lack of relevant circumstances	Failure could occur under rare and extreme circumstances	Failure probable in response to intermittent, extreme but foreseeable events	Failure is almost inevitable and possibly frequent
Frequency of occurrence in the 19 year mine-life	0	0-1	1-2	2-4	Annually

Consequences

In addition to probability, the severity of the impact or consequences of the identified failure mode must be identified and criteria developed which can be used to compare the consequences. Table 2 presents the consequence criteria evaluated in these FMEAs including: environmental, human health, changes in operations or permitting impacts, and cost.

Residual Risk

Residual risk is the combination of probability of a failure occurring and the consequences of the failure. Risk levels are typically depicted on a matrix table that compares the effects of both probability and consequences. The higher the risk level, the more justification and mitigation that is needed to lower the risk to an acceptable level. The risk categories developed for this FMEA include: extremely low, low, moderate, high and unacceptable or extreme. The risk level matrix is presented as a function of both probability and consequence in Table 3.

Table 2. Consequence Criteria for Ranking Failure Modes

Consequence	Negligible	Minor	Modest	Critical	Catastrophic
Defined	No significant affect	Minor effect on environment, human health, or project viability	Measurable effect on environment or human health resulting in intermittent or temporary operational changes with modest financial consequence	Measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	Overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability
Environmental risk	No environmental risk	Transient, minor upset requiring operational response, no design or treatment response required	Impact which can be readily addressed through minor design or treatment action	Impact which can be addressed through long term design or significant treatment action	Impact requiring major facility redesign or rebuild, requiring prolonged effort
Human health risk	No human health risk	No injuries	Possible minor injuries	Injury, no fatality	Injuries with fatalities
Resulting change in operations	No changes required	Maintenance action only	Short term loss of facility in operation requiring minor reconstructions; other resources available	Prolonged delay in facility operations requiring major reconstruction, may result in agency initiated temporary suspension of operations	Complete loss of function requiring facility replacement or loss of project viability, suspension of mine permits
Cost	< $10,000	$10,000-$50,000	$50,000-$500,000	$500,000-$1,000,000	$1-$10,000,000

Table 3. Residual risk from probability and consequences matrix.

Consequence		***Negligible***	**Minor**	**Modest**	**Critical**	**Catastrophic**
	Human Health	*No human health Risk*	*No injuries*	*Possible light injuries*	*Injury, no fatality*	*Injuries with fatalities*
	Environment	*No environmental Risk*	*Transient, minor upset requiring operational response, no design or treatment response required*	*Impact which can be readily addressed through minor design or treatment action*	*Impact which can be addressed through long term design or significant treatment action*	*Impact requiring major facility redesign or rebuild, requiring prolonged effort*
	Cost	*<$10,000*	*$10,000-$50,000*	*$50,000-$500,000*	*$500,000-$1,000,000*	*$1-$10,000,000*
Probability	***Frequency in 19 years***					
Unlikely	0	**Extremely Low** Failure under these circumstances is unlikely, no significant affects	**Low** Failure under these circumstances is unlikely, with no relevant effect on environment, human health or operations	**Moderate** Failure under these circumstances is unlikely, with measurable effect on environment or human health resulting in intermittent or temporary operational changes and modest financial consequence	**High** Failure under these circumstances is unlikely, with measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	**High** Failure under these circumstances is unlikely, with overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability
Remote	*0-1*	**Extremely Low** Highly improbable failure, with no significant affects	**Low** Highly improbable failure with no relevant effect on environment, human health or operations	**Low** Highly improbable failure with measurable effect on environment or human health resulting in intermittent or temporary operational changes and modest financial consequence	**Moderate** Highly improbable failure with measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	**High** Highly improbable failure with overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability
Infrequent	*1-2*	**Low** Failure under rare and extreme circumstances, with no significant affects	**Low** Failure under rare and extreme circumstances with no relevant effect on environment, human health or operations	**Moderate** Failure under rare and extreme circumstances with measurable effect on environment or human health resulting in intermittent or temporary operational changes and modest financial consequence	**Moderate** Failure under rare and extreme circumstances with measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	**High** Failure under rare and extreme circumstances with overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability

Table 3. Residual risk from probability and consequences matrix.

Consequence		***Negligible***	**Minor**	**Modest**	**Critical**	**Catastrophic**
	Human Health	*No human health Risk*	*No injuries*	*Possible light injuries*	*Injury, no fatality*	*Injuries with fatalities*
	Environment	*No environmental Risk*	*Transient, minor upset requiring operational response, no design or treatment response required*	*Impact which can be readily addressed through minor design or treatment action*	*Impact which can be addressed through long term design or significant treatment action*	*Impact requiring major facility redesign or rebuild, requiring prolonged effort*
	Cost	*<$10,000*	*$10,000-$50,000*	*$50,000-$500,000*	*$500,000-$1,000,000*	*$1-$10,000,000*
Probability	***Frequency in 19 years***					
Occasional	*2-4*	**Low** Failure probable in response to intermittent, extreme but foreseeable events, with no significant affects	**Low** Failure probable in response to intermittent, extreme but foreseeable events, with no relevant effect on environment, human health or operations	**Moderate** Failure probable in response to intermittent, extreme but foreseeable events, with measurable effect on environment or human health resulting in intermittent or temporary operational changes and modest financial consequence	**High** Failure probable in response to intermittent, extreme but foreseeable events, with measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	**Unacceptable** Failure probable in response to intermittent, extreme but foreseeable events, with overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability
Likely	*Annually*	**Low** Failure is almost inevitable and possibly frequent, with no significant affects	**Low** Failure is almost inevitable and possibly frequent, with no relevant effect on environment, human health or operations	**Moderate** Failure is almost inevitable and possibly frequent, with measurable effect on environment or human health resulting in intermittent or temporary operational changes and modest financial consequence	**High** Failure is almost inevitable and possibly frequent, with measurable effect on environment or human health resulting in continued operational changes with significant financial consequence	**Unacceptable / Extreme** Failure is almost inevitable and possibly frequent, with overwhelming effect on environment and human health resulting in shutdown and financial consequence affecting project viability

Site-Specific Example

Table 4 presents part of the selection processes for developing lists that characterize facilities to be examined for failure modes at the Project site. In Table 4 facilities were grouped by HDPE lined facilities with both mine water and waste storage stored on the facility, and then by the hazard ranking of the facility; other screening criteria segregated facilities with mine waste but with no water stored on them, and finally there is a screened sub-group of unlined facilities with stockpiles of soils or construction materials only.

Table 3. Mine Storage Facilities Types having Failure Modes with Potential Impacts to Water Quality

Facility Type	Characteristics	Facility Name
HDPE Lined Facilities with Mine Water and Waste Storage		
High Hazard Dam, with mine wastes and mine water storage	Storage > 50 acre-feet 60,000 m^3 (78,500 cu yds.) possible loss of human life, extensive property or ecological damage.	Cemented Tailings Facility
		Process Water Pond
Low Hazard Dam, with mine wastes and water storage	Storage <50 acre-feet 60,000 m^3, (78,500 cu yds.) Routinely pumped back to water treatment plant, pond will have almost no water except for after storm events, no expected loss of human life, damage limited to owner's property, minor ecological risk.	Contact Water Pond
Low Hazard Dam, with no mine wastes, and fresh water storage	No expected loss of human life, damage limited to owner's property.	Non-Contact Water Reservoir
HDPE Lined Facilities with Mine Waste Storage Only		
Mined Material Storage Facility	Potentially acid-generating rock, waste rock pile may not reach saturation in 2-years, seepage reports to contact water pond or diverted directly to water treatment plant.	Waste Rock Storage
		Copper-enriched Rock Storage
Unlined Stockpiles with Construction Material Storage Only		
Construction Materials	Non-acid Generating Materials.	Excess Construction
		Top- and Subsoil

With the FMEA model developed for probability, consequence and residual risk, each facility and process was subjected to the analysis, identifying failure modes and probability of their occurrence, the consequences of the failure and then analyzing the resulting residual risk. For components with high residual risk, mitigations were developed by which processes were modified and facilities redesigned to mitigate the identified risk. This analysis produced extensive tables of data inputs and results. At the end of the analyses of the FMEA study, the early unmitigated developed processes and facility designs were compared against the mitigated counterparts and compared for residual risk. Table 5 is a portion of the FMEA analysis with a selected group of failure modes looking at various facilities and processes by comparing the unmitigated alternative for facility design or select processes with the mitigated alternative. In Table 5 the transition from warm to cool colors represent transitions from likely to unlikely occurrence of a failure mode, and from catastrophic or extreme to negligible consequences.

Table 5. Comparison of FMEA for Select Unmitigated and Mitigated Processes or Facility Construction Scenarios

Failure Mode	Cause	Facility Name	Probability	Consequence	Tintina Proposed Design Mitigation	Revised Probability	Revised Consequence
			Unmitigated			Mitigated	
Overfilling and Discharge with or without embankment failure	Inadequate Storage Capacity	Tailings (CTF)	Remote	Catastrophic	Probable Maximum Flood Event Storage	Unlikely	Catastrophic
		Process Water (PWP)	Remote	Catastrophic	Probable Maximum Flood Event Storage Plus 1:500 Year Event Storage of CTF	Unlikely	Catastrophic
		Contact Water Pond (CWP)	Infrequent	Critical	1:200 Year Event Storage	Remote	Critical
		Noncontact Water (NCWR)	Infrequent	Modest	1:200 Year Event Storage	Unlikely	Negligible
Overfilling and Discharge with or without embankment failure	No Pump-back Capability	Tailings (CTF)	Remote	Catastrophic	Pump back 1:500 year event to Process Water Pond	Unlikely	Catastrophic
		Process Water (PWP)	Remote	Catastrophic	none	Unlikely	Catastrophic
		Contact Water Pond (CWP)	Infrequent	Critical	Automatic Pump-back to Water Treatment or Process Water Pond, only minimal storage daily, often dry	Unlikely	Critical
		Noncontact Water (NCWR)	Infrequent	Modest	Spillway Controlled Discharge of fresh water > 1:200 Year Event	Unlikely	Negligible
t							
Embankment Failure. Geotechnical Instability	Foundation Design Failure	Tailings (CTF)	Remote	Catastrophic	Stage 1 FOS 2.5/2.3 (up/downstream) (min 1.5) Stage 2 FOS 2.5/2.3 (up/downstream) (min 1.5)	Unlikely	Minor
		Process Water (PWP)	Remote	Catastrophic	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.5 (up/downstream)(min 1.5)	Unlikely	Catastrophic
		Contact Water Pond (CWP)	Infrequent	Critical	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.5 (up/downstream)(min 1.5)	Unlikely	Critical
		Noncontact Water (NCWR)	Infrequent	Modest	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.0 (up/downstream)(min 1.5)	Unlikely	Modest
Embankment Failure Seismic Instability	Earthquake	Tailings (CTF)	Infrequent	Modest	Stage 1 FOS 1.6/1.5 (up/downstream) (min 1.2) Stage 2 FOS na/1.5 (up/downstream) (min 1.2)	Unlikely	Modest
		Process Water (PWP)	Infrequent	Catastrophic	Constr. FOS 1.6/1.6 (up/downstream) (min 1.2) Opn. FOS na/1.6 (up/downstream) (min 1.2)	Unlikely	Catastrophic
		Contact Water Pond (CWP)	Infrequent	Critical	Constr. FOS 1.6/1.6 (up/downstream) (min 1.2) Opn. FOS na/1.6 (up/downstream) (min 1.2)	Unlikely	Critical
		Noncontact Water	Infrequent	Modest	Constr. FOS 1.6/1.6 (up/downstream) (min	Unlikely	Modest

Table 5. Comparison of FMEA for Select Unmitigated and Mitigated Processes or Facility Construction Scenarios

Failure Mode	Cause	Facility Name	Probability	Consequence	Tintina Proposed Design Mitigation	Revised Probability	Revised Consequence
			Unmitigated			Mitigated	
		(NCWR)			1.2) Opn. FOS na/1.2 (up/downstream) (min 1.1)		
Embankment Failure Geotechnical Instability	Liquefaction of tailings	Tailings (CTF)	Infrequent	Critical	Tailings are cemented; No significant water stored on tailings facility except after storm events	Unlikely	Negligible
		Process Water (PWP)	na	na	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.5 (up/downstream)(min 1.5)	na	na
		Contact Water Pond (CWP)	na	na	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.5 (up/downstream)(min 1.5)	na	na
		Noncontact Water (NCWR)	na	na	Constr. FOS 2.5/2.5 (up/downstream)(min 1.3) Opn. FOS na/2.0 (up/downstream)(min 1.5)	na	na
Seepage of leachate	Inadequate or no liner	Tailings (CTF)	Infrequent	Critical	2, 100 mil HDPE Liners with intermediary geogrid, overlying and underlying cushion layer, minimal water on facility	Unlikely	Modest
		Process Water (PWP)	Occasional	Critical	2, 100 mil HDPE Liners with intermediary geogrid, overlying and underlying cushion layer	Remote	Critical
		Contact Water Pond (CWP)	Infrequent	Critical	2, 100 mil HDPE Liners with intermediary geogrid, overlying and underlying cushion layer, little water stored on pond	Unlikely	Modest
		Noncontact Water (NCWR)	na	na	60 mil HDPE upstream embankment liner, Seepage inherent in design from reservoir	na	na
		Waste Rock Storage (WRS)	Infrequent	Modest	100-mil HDPE liner, with overlying cushion layer and underlying foundation drain, 2-3 year time period, only toes saturated	Unlikely	Minor
		Copper-enriched Rock Storage (OS)	Infrequent	Modest	100-mil HDPE liner, with overlying cushion layer and underlying foundation drain, 13 year period	Remote	Modest
Seepage of Leachate	No foundation drain pump back	Tailings (CTF)	Infrequent	Critical	Foundation drainage layer and piping, foundation drain pond with pump-back system, minimal water on facility	Unlikely	Minor
		Process Water (PWP)	Occasional	Critical	Foundation drainage layer and piping, foundation drain pond with pump-back system	Remote	Critical
		Contact Water Pond (CWP)	Infrequent	Critical	Foundation drainage layer and piping, foundation drain pond with pump-back system, little water stored in pond	Remote	Minor
		Noncontact Water (NCWR)	na	na	Foundation drainage layer and piping, foundation drain pond with pump-back system	na	na
		Waste Rock Storage	Infrequent	Modest	Foundation drainage layer and piping,	Unlikely	Minor

Table 5. Comparison of FMEA for Select Unmitigated and Mitigated Processes or Facility Construction Scenarios

Failure Mode	Cause	Facility Name	Probability	Consequence	Tintina Proposed Design Mitigation	Revised Probability	Revised Consequence
			Unmitigated			Mitigated	
		(WRS)			drainage collection on top of HDPE liner to CWP, pump back CWP to WTP or PWP		
		Copper-enriched Rock Storage (OS)	Infrequent	Modest	Foundation drainage layer and piping, drainage collection on top of HDPE liner to CWP, pump back CWP to WTP or PWP	Remote	Modest
Tailings Spill	Mill to CTF Pumping Line Failure	Tailings (CTF)	Occasional	Minor	Double lined pumping line steel inside HDPE pipe; pipe in HDPE lined trench or on top of CTF HDPE Liner.	Unlikely	Negligible
Contaminated Discharge from Mine opening	Underground mine water discharge to surface water in closure, risks of future blow-outs of contaminated water and sediment	Mine Portal and Vent Raises, Life of Mine and Closure	Infrequent	Critical	All mine openings (portal and ventilation raises) located above regional groundwater table, no possibility of discharge to surface water in closure	Unlikely	Negligible
Contamination of Air and Laydown areas during Concentrate Shipping	Open trucks or multiple laydown areas during shipping of concentrate	Along highways and in off-site laydown-intermediate shipping storage areas	Likely	Critical	Concentrate shipping is closed and sealed cargo containers by truck and rail	Unlikely	Negligible
Contact Water Collection and Transport	Failure to collect or leakage	All facilities	Occasional	Minor	Surface contact water from areas immediately adjacent to facilities reports to foundation drain ponds for pump-back to facilities or contact water reports to lined collection ditches or pipelines to CWP	Infrequent	Negligible
Storm Water from Stockpiles	Failure to trap sediments	All facilities including stockpile	Occasional	Minor	Storm water reports to storm water collection basins for infiltration or dispersion, silt fencing and other BMPs on all downgradient construction disturbances associated with stockpiles.	Infrequent	Negligible

Schematic Representation of FMEA Residual Risk Assessment

Figure 1 is a schematic that plots failure probability vs. consequence to define fields of residual risk, as an example of how specific case studies will be examined for the remainder of alternatives and mitigations considered. On Figure 1 the categories of residual risk are ranked as very low, low, moderate, high and extreme or unacceptable.

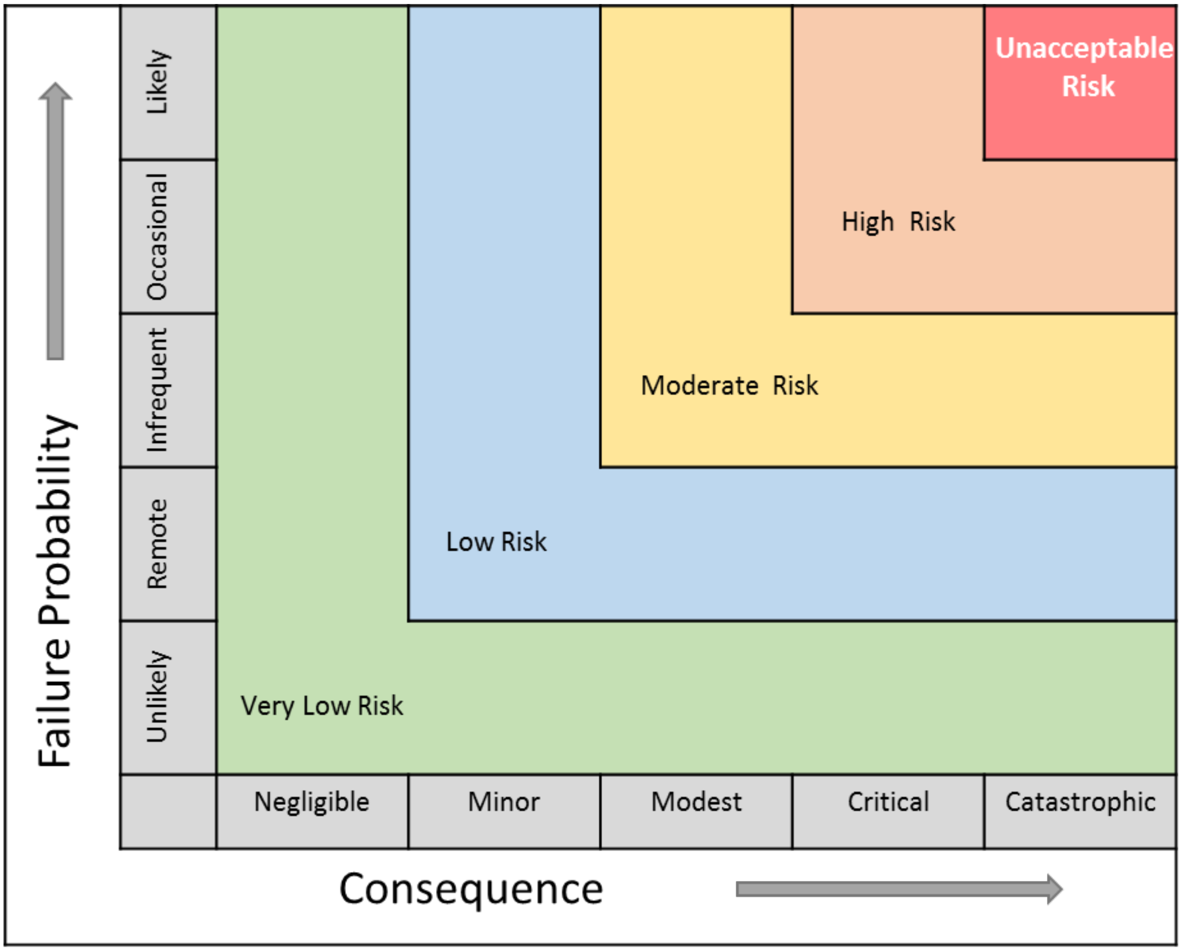

Figure 1. Schematic plotting probability vs. consequence to define fields of residual risk

On the following graphics each of the failure modes from Table 5 is sequentially examined first by identifying the failure mode and its cause, and then by looking at each facility to be compared. First the facility is ranked for the probability and consequences and the residual risk for the unmitigated condition. Then the proposed mitigations are enumerated, and finally the same facility is ranked for the probability of the failure mode and it consequences under the mitigated set of conditions. Graphically each of the facilities are labeled with unmitigated ranking shown in red font and the mitigated ranking shown in green font. Finally an arrow is drawn between the two rankings to illustrate the change in residual risk that results from implementation of the mitigations. Figures are titled as a function of the failure mode.

The first set of five figures (Figures 2, 3, 4, 5, and 6) considers mine facilities that store both mine wastes and water for various failure modes.

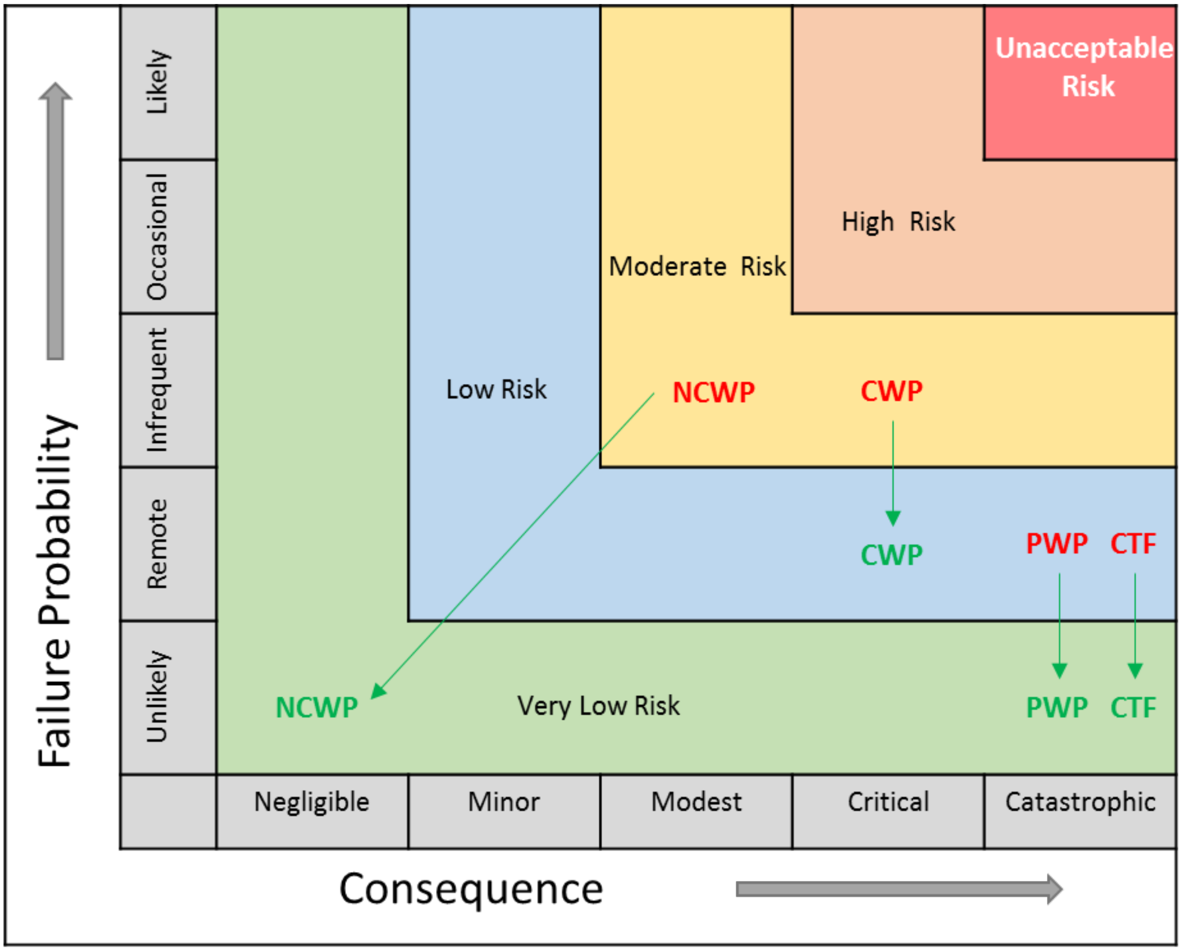

Figure 2. Overfilling of facility and discharge resulting from inadequate water storage capacity

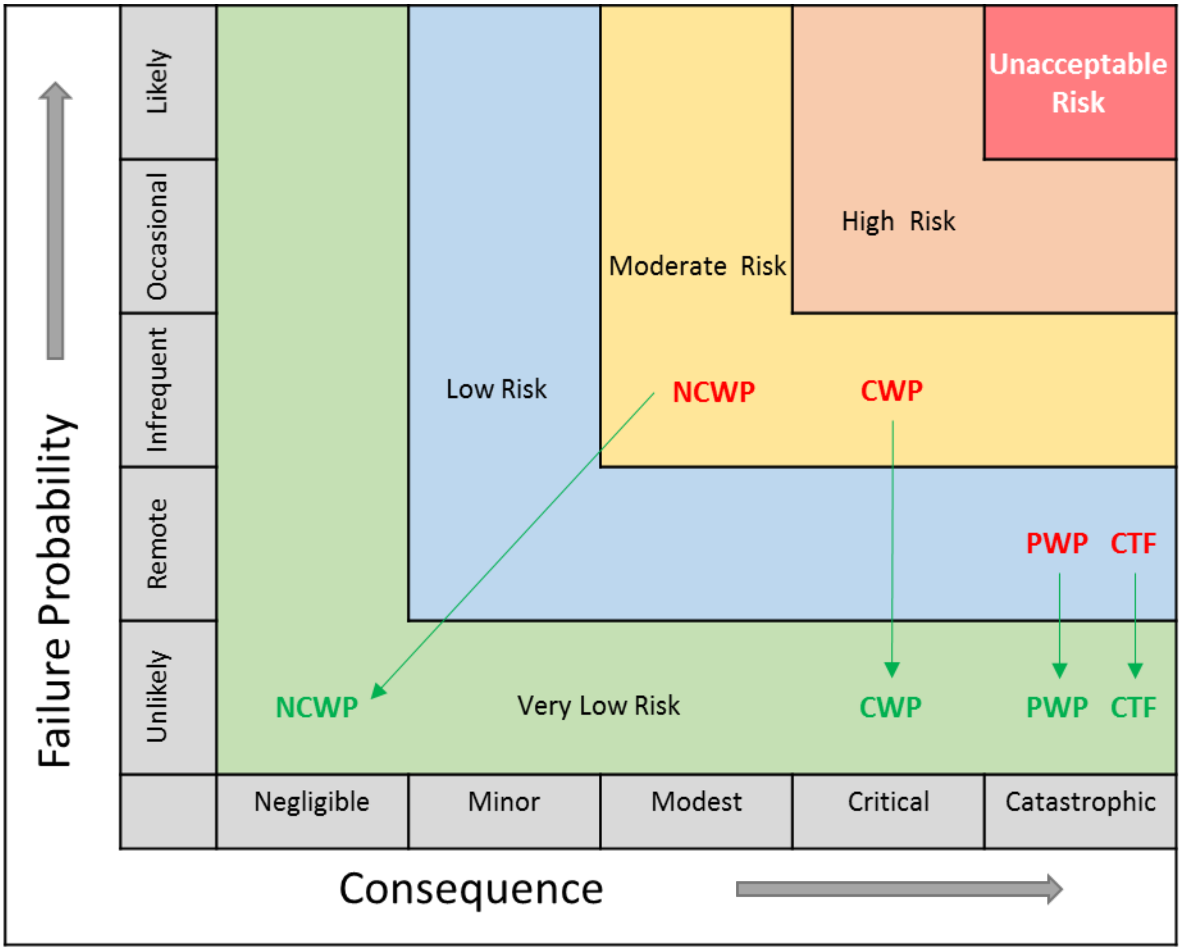

Figure 3. Overfilling of facility and discharge resulting from lack of pump-back capability

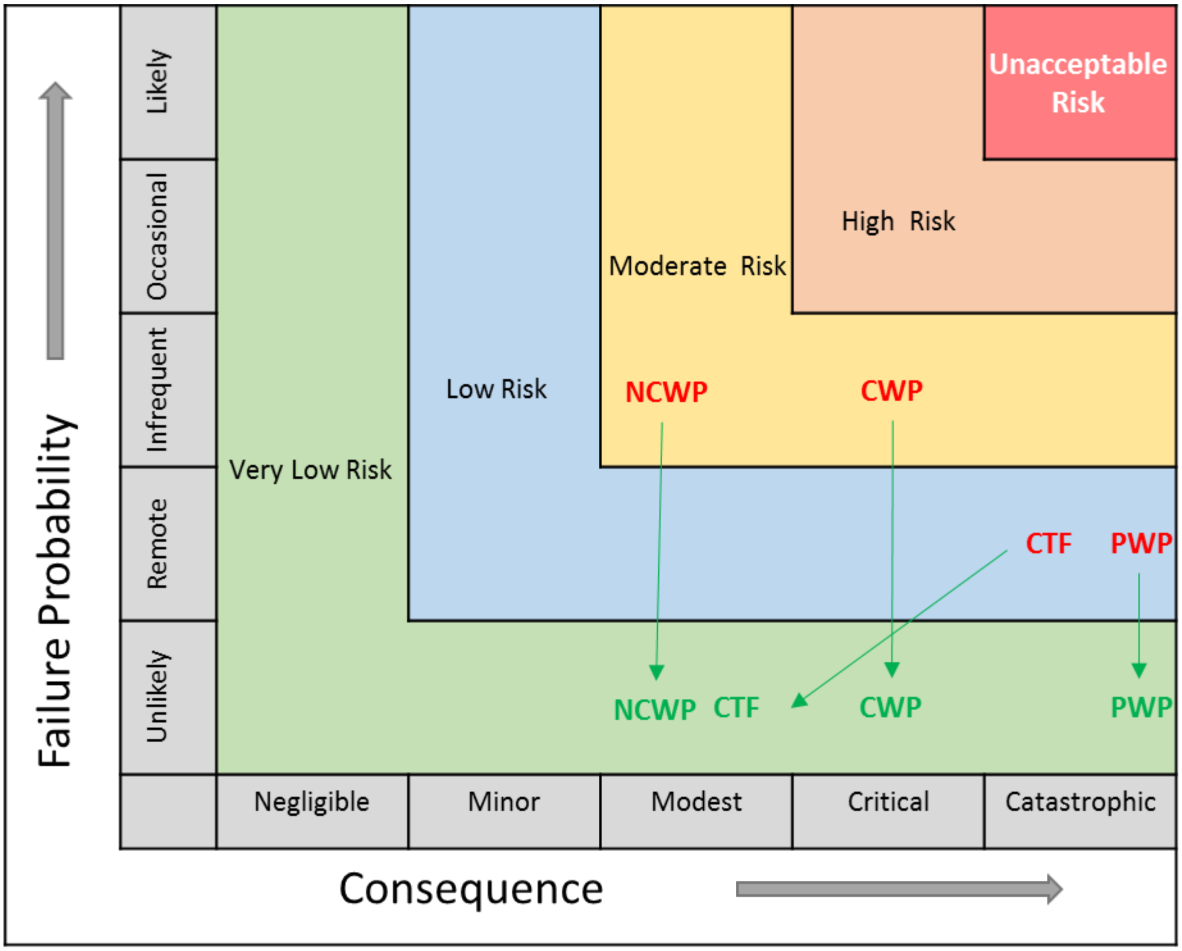

Figure 4. Discharge resulting from facility foundation design failure

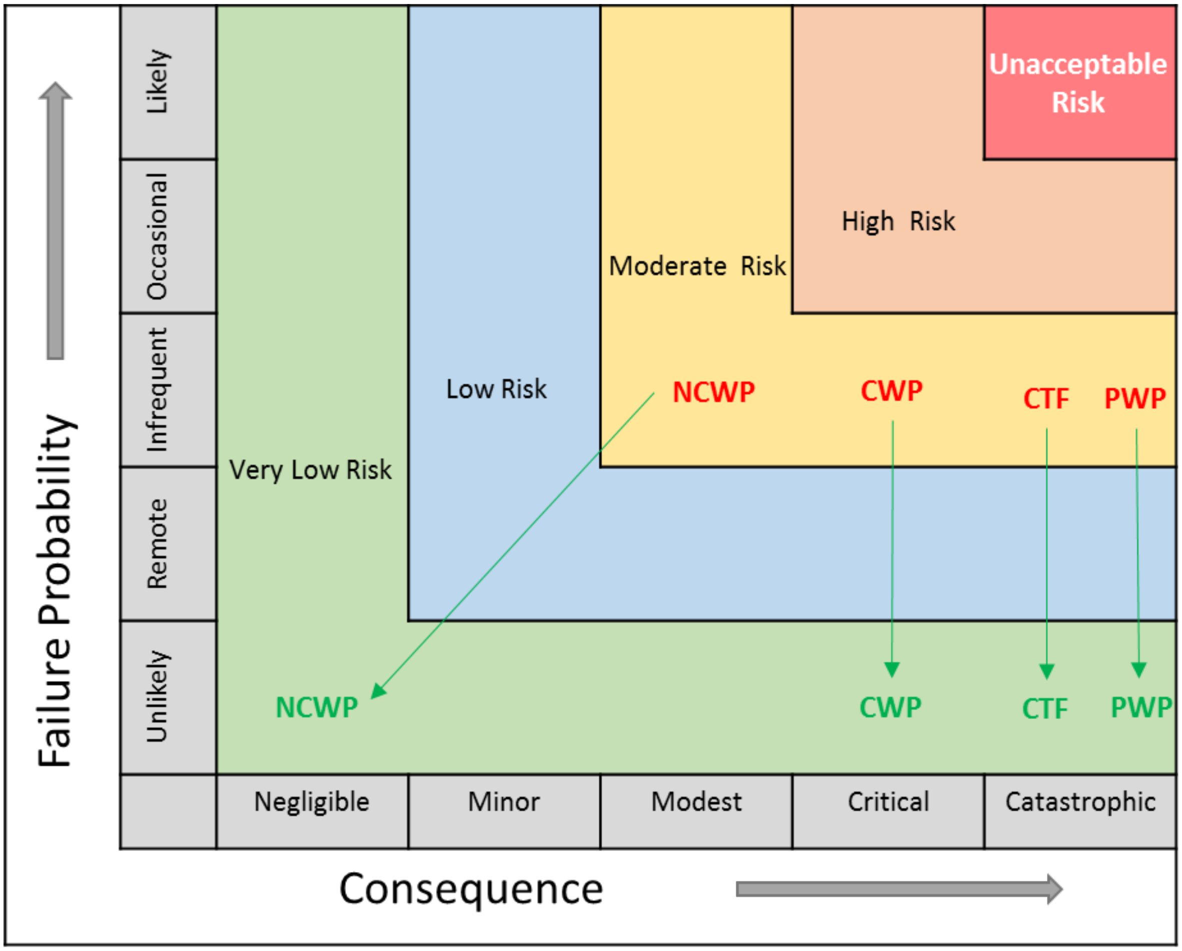

Figure 5. Discharge resulting from facility failure due to earthquake

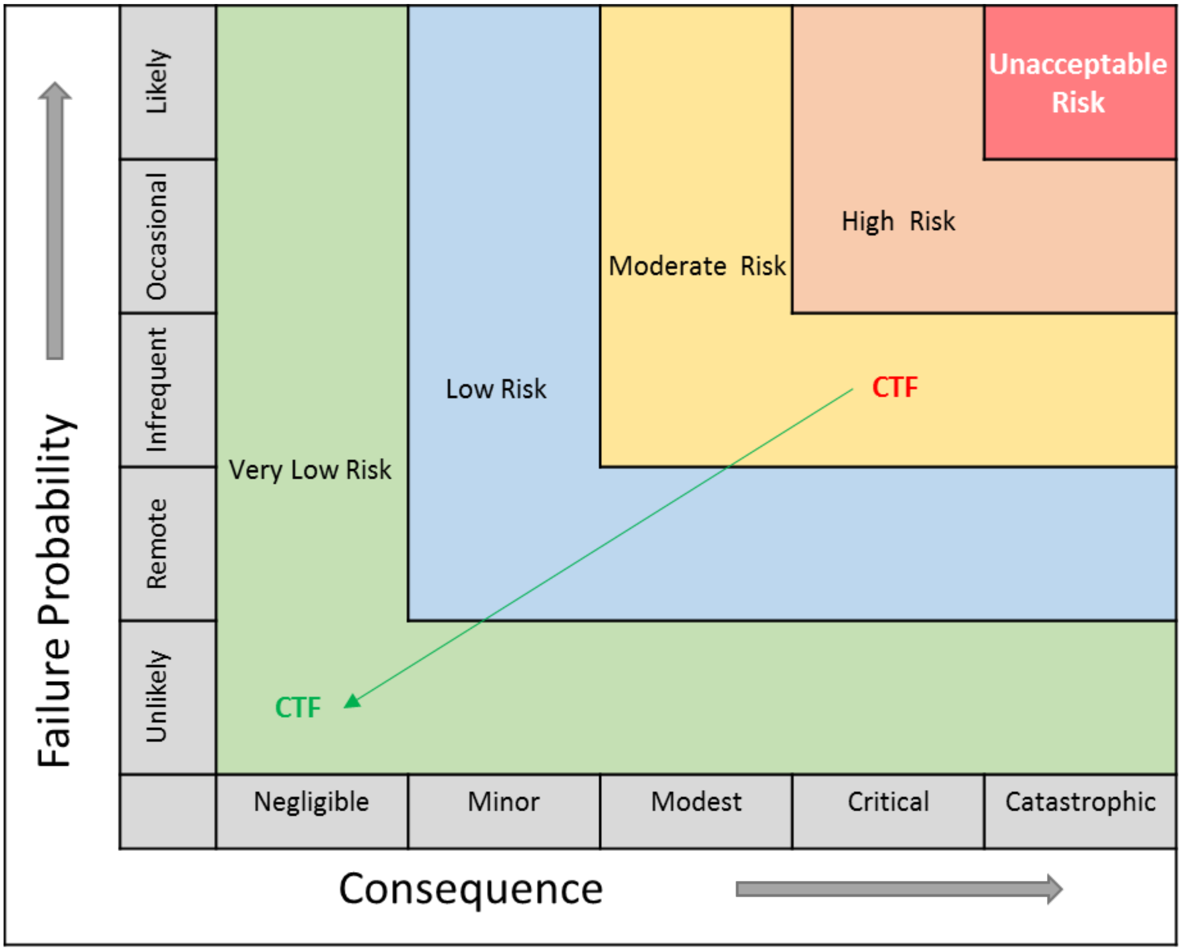

Figure 6. Discharge resulting from facility failure due to liquifaction

The next two figures (Figures 7 and 8) consider mine facilities that store only mine wastes (no ponds of water) for various failure modes. Note that the Temporary WRS facility may not reach saturation or generate seepage in as little as its proposed 2-years of operation (prior to reclamation and closure).

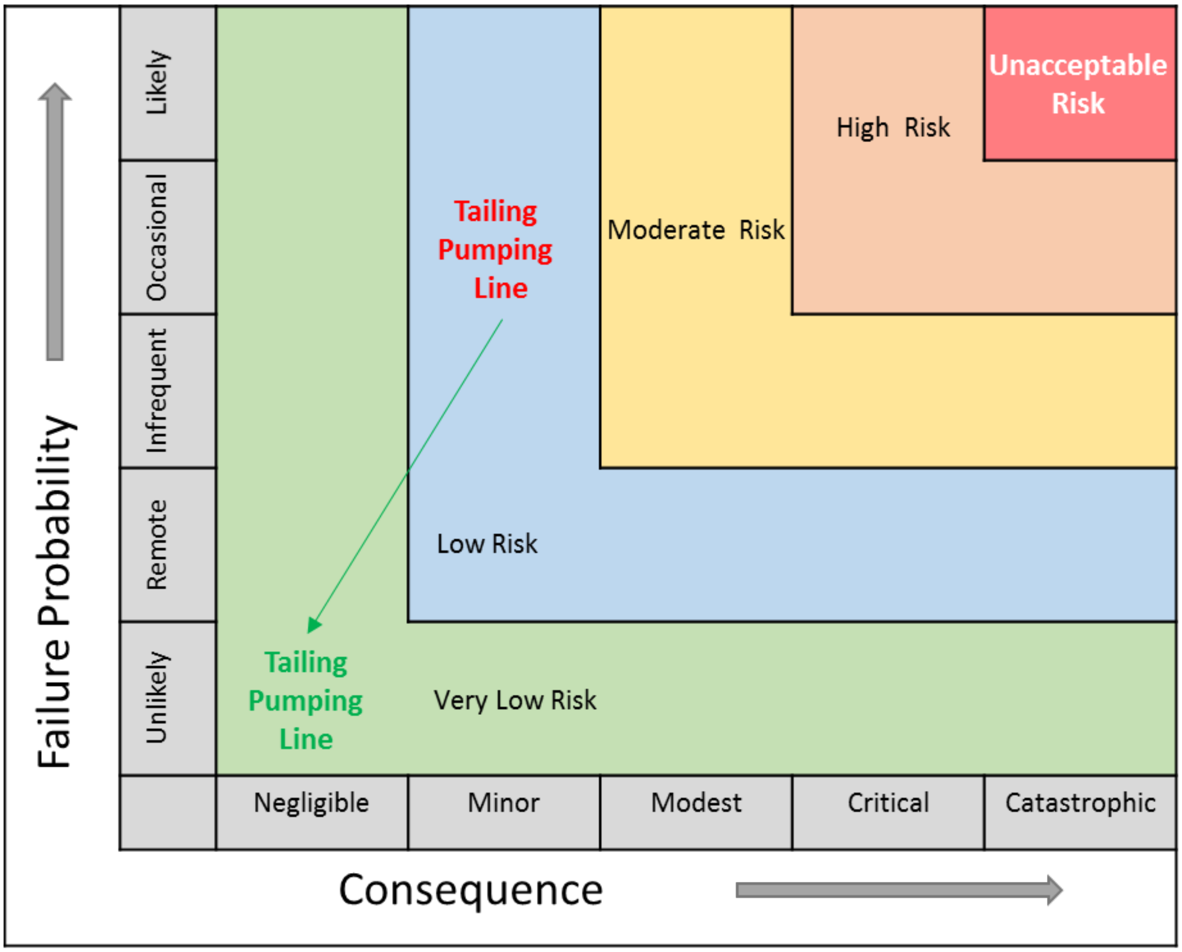

Figure 7. Discharge resulting from tailings pumping line failure

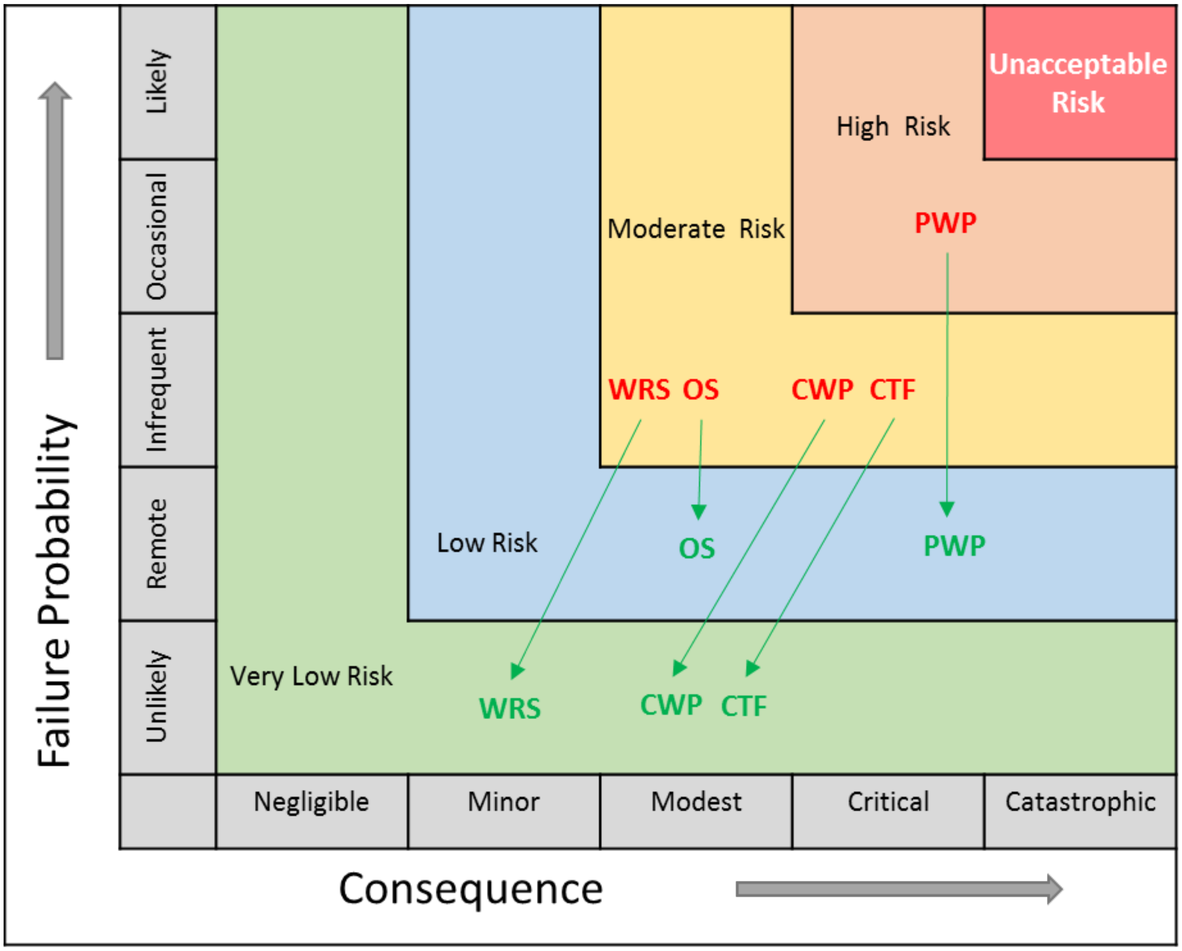

Figure 8. Discharge of seepage resulting from inadequate or no liner

Figures 9 examines facilities or ditches whose BMPs fail to control either contact water collection or storm water and sediment discharge.

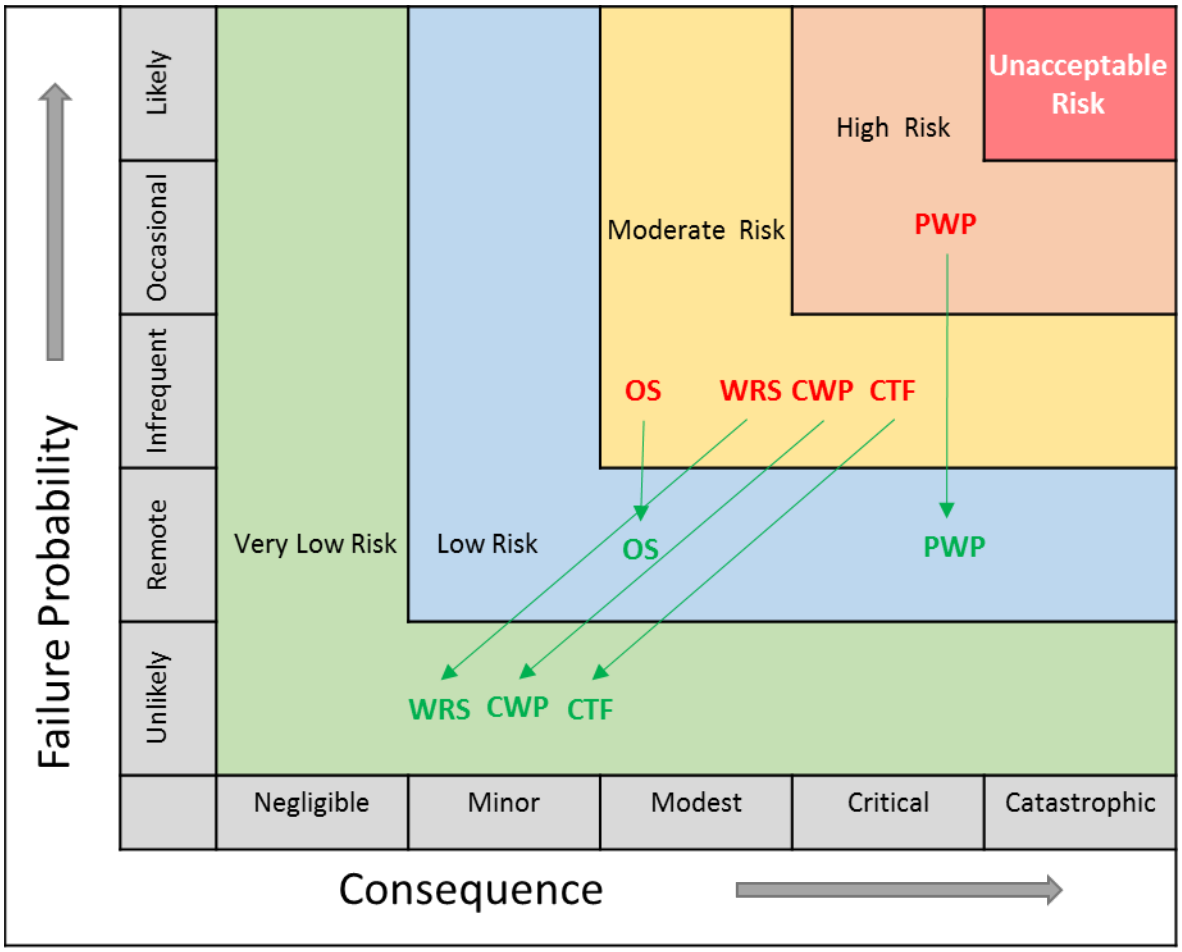

Figure 9. Discharge of seepage resulting from no foundation pump-back

Figures 10 examines facilities or ditches whose BMPs fail to collect either contact water or storm water sediment.

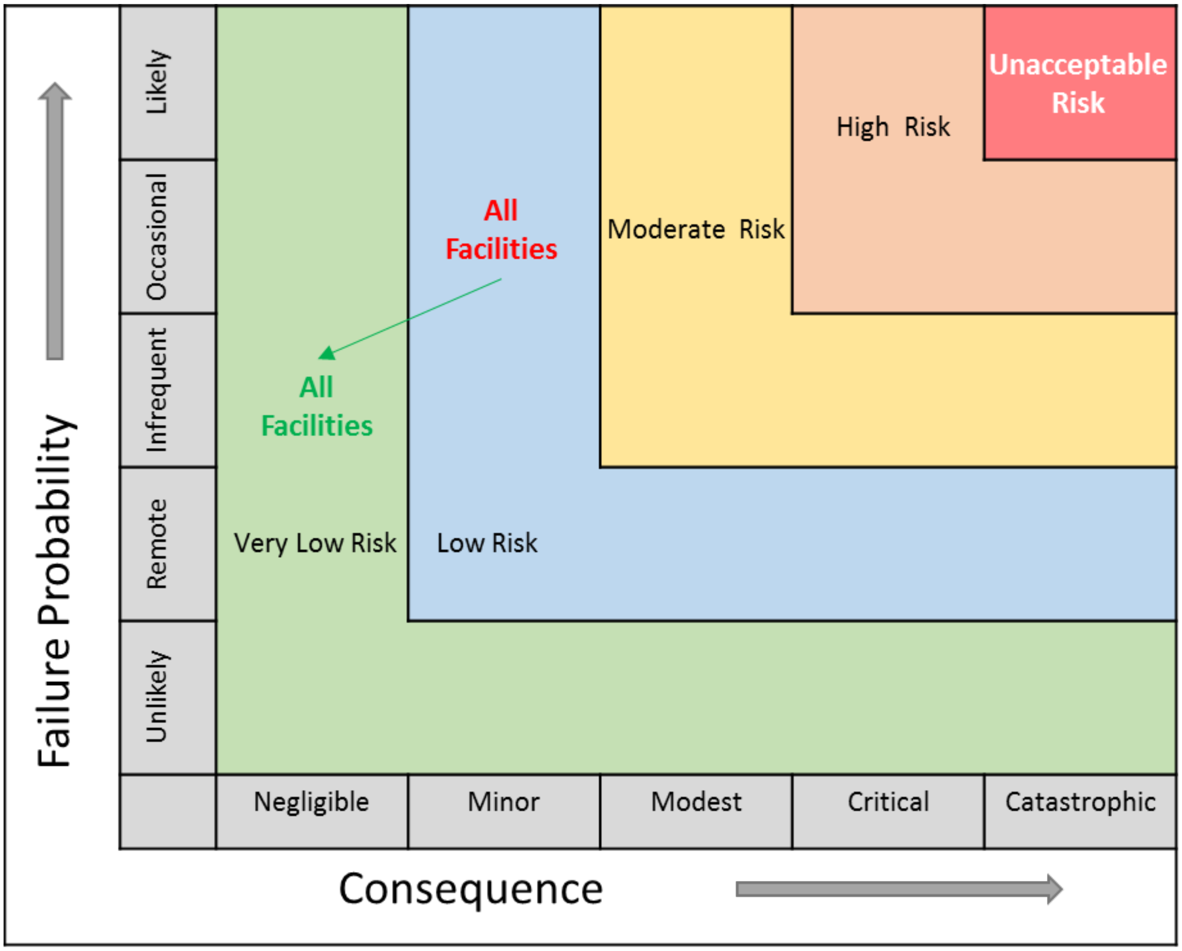

Figure 10. Discharge resulting from failure to collect contact water sediment

Figure 11 examines the resultant risk from failure to site mine openings above the water table.

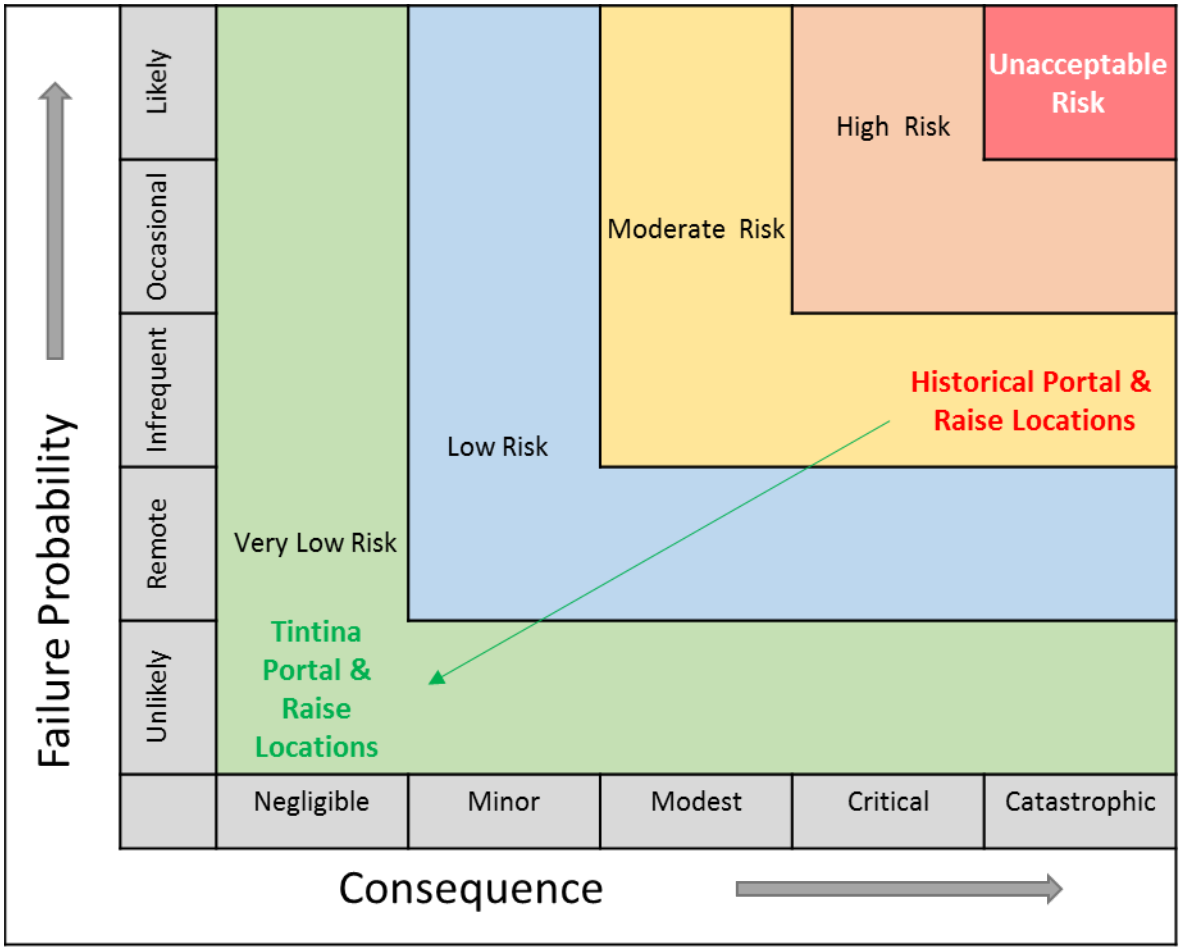

Figure 11. Discharge from mine opening resulting from portal and raise locations

The final figure (Figure 12) examines the resultant risk to air quality and potentially to surface water from failure due to shipping concentrate in open trucks with multiple laydown areas along the transport route vs shipping concentrate in closed and sealed shipping containers.

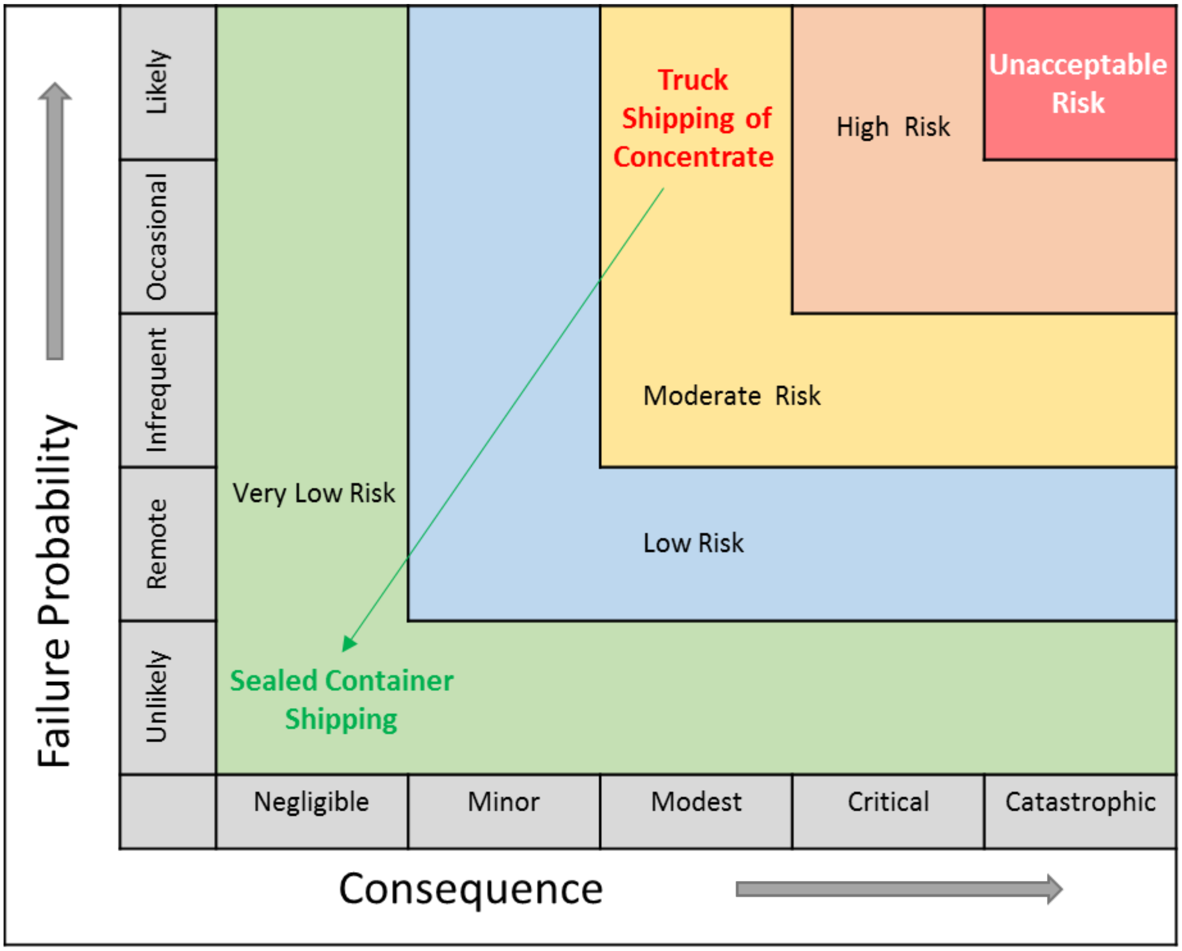

Figure 12. Risk of contaminating air or laydown areas during concentrate shipping

Summary

A few examples of how selected failure modes for operational processes, facility siting, and facility construction criteria can be evaluated using FMEA are presented above. This analysis was used to identify and then propose mitigations to more typical historical mine planning in order to enhance the success of this Project. The FMEA analysis documents that the incorporation of these mitigations consistently and significantly reduces residual risk of failure. The analysis allows the selection of improved processes, better selection of facility locations, and incorporation of improved changes in construction or design methods. The list of proposed mitigations at the beginning of Section 5.1 of the Mine Operating Permit Application points out some of the highlights of this planning process that Tintina believes will lead to a successful mining operation that substantially mitigates impacts to human health and the environment.